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*Published in:*  
Agricultural and Forest Meteorology

*Link to article, DOI:*  
[10.1016/j.agrformet.2013.01.004](https://doi.org/10.1016/j.agrformet.2013.01.004)

*Publication date:*  
2013

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Bruhn, D., Larsen, K. S., de Dato, G. D., Duce, P., Zara, P., Beier, C., Schmidt, I. K., Clausen, S., & Mikkelsen, T. N. (2013). Improving the performance of infrared reflective night curtains for warming field plots. *Agricultural and Forest Meteorology*, 173, 53-62. <https://doi.org/10.1016/j.agrformet.2013.01.004>

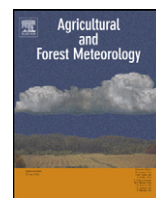
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## Improving the performance of infrared reflective night curtains for warming field plots

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### ARTICLE INFO

#### Article history:

Received 6 August 2012

Received in revised form

19 December 2012

Accepted 15 January 2013

#### Keywords:

Climate change

Ecosystem manipulation

Global warming

Infrared radiation

IR curtains

Nighttime warming

Passive warming

Soil warming

### ABSTRACT

Infrared reflective (IR) curtains have been widely used to obtain passive nighttime warming in field ecosystem experiments in order to simulate and study climate warming effects on ecosystems. For any field installation with IR-reflective curtains in an ecosystem the achieved heating effect depends on the heat gain determined by the stored energy during daytime (incoming radiation can be used as a proxy) the heat conservation determined by the IR-reflective effect of the curtains (cloudiness can be used as a proxy) and the heat loss determined by convectional heat loss (wind speed can be used as a proxy). In this study, we demonstrate some feasible avenues for improving the achieved temperature increase ( $\Delta T$ ) when using IR-reflective curtains at field scale by attacking the three main factors determining the efficiency of the curtains: (i) improving the long wave IR reflection by the curtains, (ii) insulating the curtains and (iii) reducing the lateral wind speed. We provide experimentally based replies to the major concerns raised in the literature about the passive nighttime warming method. We show (a) that using IR-reflective curtains during night does in fact not result in nighttime warming only as there is a small carryover ( $<0.5^\circ\text{C}$ ) into the following daytime, and (b) although the employment of IR-reflective curtains at nighttime may alter the RH, it is a small change and not always in the same direction.

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### 1. Introduction

Climate is changing leading to changes in main factors controlling plant growth. This will impact ecosystem structure and functioning and in turn, through feedback mechanisms, potentially accelerate the climatic changes (Solomon et al., 2007). Due to lack of understanding of the complex ecosystem processes and interactions involved, ecosystem models differ in their predictions of ecosystem responses to climate change, and in their assessment of which factors play the dominant roles for the ecosystem feedback (e.g. Luo et al., 2008). High priority should therefore be given to ecosystem experiments and long-term observations in order to improve our understanding of ecosystem processes and further develop ecosystem models (e.g. Beier et al., 2004). In order to obtain validation data for such models, it is essential to simulate

climate changes at field scale with effective, reliable, and realistic techniques.

Over recent decades, several different techniques have been applied at the ecosystem scale for studying the effects of warming. These may be divided into techniques adding heat (e.g. warming cables, infrared heaters and heated chambers) and systems retaining heat (e.g. reflective curtains), i.e. “active” and “passive” techniques, respectively (cf. Aronson and McNulty, 2009 for latest review). In 1998 passive warming systems were installed in four shrubland ecosystems across Europe in Denmark, Wales, The Netherlands, and Spain (CLIMOOR project, Beier et al., 2004) and in 2001 also in Hungary (Bakonyi et al., 2007) and Italy (de Dato et al., 2008) under the EU project VULCAN (Beier et al., 2008). These systems were custom made and employed infrared reflective curtains (aluminum strips knitted into a high-density polyethylene mesh) covering the vegetation at nighttime. The temperature increase achieved after the first two years of treatment in the CLIMOOR project by this nighttime “passive” warming technique was about  $0.4\text{--}1.2^\circ\text{C}$  (increase in minimum air and soil temperatures) (Beier et al., 2004). As typically experienced with many types of field based custom made experimental systems, reliability is a significant issue. Therefore, in the following generation of

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“passive” nighttime ecosystem warming application a commercially available curtain system was chosen (white, water-proof curtain woven acrylic cloth) (CLIMAITE project, Mikkelsen et al., 2008). In CLIMAITE the average increase of soil and air temperature at nighttime was equal to 0.6 °C and 1.4 °C, respectively, after the first two years of treatment.

The passive nighttime warming has been claimed to be advantageous by imitating the diurnal and intraannual warming pattern associated with climate change realistically and by being non-intrusive (Beier et al., 2004). Recently, Aronson and McNulty (2009) reviewed published literature on appropriate experimental ecosystem warming methods and concluded that the method of “passive” nighttime warming, as applied in the CLIMOOR and CLIMAITE experiments, is one of the most realistic and also applicable. However, Amthor et al. (2010) raised several strong concerns regarding “passive” nighttime warming of ecosystems. One issue was related to a general concern about all types of warming experiments because there is generally no control of air humidity in conjunction with warming of ecosystem and air. Warming could lead to unwanted decreases in air relative humidity (RH) and thereby vapour pressure deficit (VPD). Another issue was the premise of ‘nighttime-only warming’ as being particularly relevant in a climate change context was challenged and accused for being of ‘limited value to understanding effects of future warming on terrestrial ecosystems’ because the global trend (decline) in diurnal temperature range (DTR) disappeared after the year 1980 (Amthor et al., 2010).

In addition to the recent discussion in the literature of passive nighttime warming, another issue relates to the amplitude of warming. The temperature increase obtained by the passive warming technique so far has been in the lower range of the climate change scenarios (e.g. IPCC, 2007) and also low relative to the inter annual variability at most sites leading to difficulties in identifying impacts of the warming on ecosystem processes. An improvement of the passive nighttime warming with IR-reflective curtains is therefore desirable. Three logical avenues to conserve the stored heat from daytime incoming radiation would be (i) improving the long wave IR reflection by the curtains, (ii) reducing the heat removal by reducing the lateral wind speed, and (iii) to conserve heat by insulating the curtains. All of these would, in terms of nighttime heat storage, improve the net radiation balance and reduce the heat lost by convection and/or conduction.

In this paper we aimed to (i) experimentally evaluate potential improvements of the passive warming by IR-reflective curtains and (ii) provide experimentally based data to evaluate the major concerns raised by Amthor et al. (2010) about this method. We address the aims of the paper by comparing results from the IR-reflective curtain installations in CLIMOOR and CLIMAITE as well as with results from a new test installation within the INCREASE framework (<http://www.increase-infrastructure.eu>) designed to investigate above mentioned potential avenues for improving the passive nighttime warming with IR-reflective curtains.

## 2. Materials and methods

Field tests were conducted at two Danish field sites (Risø-DTU and Brandbjerg) and one Italian field site (Porto Conte). At Risø-DTU, we applied hard aluminum lamella curtains and tested a range of new initiatives to improve the existing method of IR-reflective curtains. Data from DTU were furthermore used to analyze impacts of passive nighttime warming on DTR. At Brandbjerg, we applied white fabric curtains. At Porto Conte, we applied aluminum mesh curtains and data from this site were used for our analysis of RH. Cloud cover (eight classifications from clear sky to complete cloud cover) of sky) data was kindly provided by the Danish

Meteorological Institute from Tune Airport (55°35′18″N, 12°07′18″E) nearby the Danish field sites and collected by the webservice [www.eurometeo.com](http://www.eurometeo.com) for the Italian site.

### 2.1. Risø-DTU, Denmark

The experimental site at Risø-DTU (55°41′19″N, 12°06′18″E) which started in August 2010, included 9 rectangular plots (3.2 m × 3.4 m) surrounded by a steel frame. The plots were positioned in three rows and each row contained three plots with the longest sides of the plots pointing in East-West direction. Three different warming systems were applied in three replicates, one of each system in each row. The three systems were:

- an automatic curtain build of hollow double layer aluminum lamellas (Alu-lamellas) positioned horizontally c. 75 cm above the soil surface on the steel frame surrounding the plot
- a similar system but with polystyrene filled aluminum lamellas (AluIns-lamellas) positioned horizontally c. 75 cm above the soil surface on a steel frame
- a control plot without the curtain, but with the steel frame and an aluminum mock-up simulating the physical design of the enclosure for the motor and spring

The curtain systems were constructed from modified roller shutters (GNS Branddeuren en Rolliuken B.V., NL-1521 RP Wormerveer, The Netherlands), and consisted of aluminum lamellas rolled on a motor powered shaft covered by an aluminum box for shelter in the East end and a spring tensioned pull shaft also covered by an aluminum box in the West end. The motor powered shaft operated the “roll out” and “roll in” of the lamellas. A wire system connected the lamellas to the spring tensioned pull shaft in order to pull the lamellas across the plot during “roll out”. During “roll out” and “roll in” the lamellas slid on supportive nylon tracks situated on the two longest sides (South and North sides). One plot in each row served as a control plot without the lamella construction, but with a steel frame and an aluminum mock-up simulating the motor and spring system enclosures.

The motors operating the lamellar curtains were controlled by a number of day length and weather condition parameters programmed and stored in a FL1D-H12RCE Idec SmartRelay ([www.idec.com](http://www.idec.com)). The SmartRelay received input data from a timer (Müller, SC28.13 PRO, Germany) controlling the day length, a precipitation sensor, an IR-light barrier (A. Thies GmbH & Co. KG, Germany), a wind speed sensor (Windwächter Plus 500, Vestamatic, Germany) and a rain/dew sensor (Regenwächter V2.0, Vestamatic, Germany). The curtains were rolled out to cover the vegetation 30 min after sunset and retracted 30 min before sunrise except for the following events:

- Rain – curtains were retracted in case of rain during the Night (sensitivity <0.1 mm).
- Wind – the curtains were removed at high wind speeds (>10 m s<sup>-1</sup>).
- Dewfall – the curtains were removed in case of dewfall (max 30 min.).

The response time for the curtains, from full coverage of the plots to a complete withdrawal or vice versa was 16 s. All curtain operations and the event triggering the operations were logged on a Squirrel datalogger (453, Eltek Limited, Haslingfield, UK).

#### 2.1.1. Warming tests

In addition to the basic automatic nighttime operation of the curtains a set of manual operations were tested in campaigns in order to identify possible improvements of nighttime warming

and/or interactions among controlling factors. The following set-ups were conducted in different combinations:

- (1) *Additional insulation of the curtains*: extruded polystyrene blocks (c. 10 cm × 60 cm × 80 cm,  $H \times L \times W$ ) were placed on top of the polystyrene filled aluminum lamellas (Alulns-lamellas) after the curtains were pulled out at sunset and removed before withdrawal of the curtains at sunrise.
- (2) *Extension of the cover time of the curtains (pre-sunset)*: The curtains were operated to cover the plots earlier in order to cover the plots for a longer period.
- (3) *Reduced horizontal wind movement underneath the curtains*: Vertical wind screens (0.9 m × 4.0 m,  $H \times L$ ) made of a steel frame and plastic sheeting placed (a) 1 m from edges of the plots on three sites (North, South and West) and (b) just at the edge on the of three sides (North, South and West). The wind screens were put up simultaneously with the pull out of the curtains and removed after withdrawal of curtains.
- (4) *Additional heat storage*: Water filled containers (5 l polyethylene HD, 72 per plot, c. 23 cm × 18 cm × 12 cm,  $H \times L \times W$ ) were placed on three plot edges (North, South and West, 24 per edge) and kept in the same position during the campaign. The water filled containers add c. 970 kJ °C<sup>-1</sup> m<sup>-2</sup> heat storage capacity to the system.

### 2.1.2. Site and experimental control measurements

A weather station situated in the middle of the experimental area collected basic meteorological data at 2 m height (photosynthetic active radiation (PAR), temperature (PT-100), precipitation, wind speed and wind direction). Data were measured every minute and stored as 10 min averages with minimum and maximum on a data logger (CR1000, Campbell Scientific, USA).

Within each experimental plot parameters were measured to check and document the treatments and their effects on the physical and climatic conditions. Temperature was measured in a vegetation free zone in each plot by the use of Pt100 sensors (1/3 DIN kl. B, TF-25 OD 6 mm, stainless steel IP67 Pt100 1/3 DIN kl. B, Termokon, Mittenaar, Germany). The sensors were placed in the air (+20 cm) inside radiation shielding (#82101, Columbia Weather Systems, Inc., USA) and 5 cm in the ground in vegetation free plastic cylinders (Ø 15 cm, H 15 cm) filled with coarse quartz sand (grain size 0.7–1.2 mm) and covered with a coarse metal mesh. Temperature and volumetric soil water content were measured in the soil by the use of Decagon 5 TM probes (Decagon devices Inc., USA) installed with the long side in horizontal position and the flat side in vertical position. Measurements were conducted every minute and stored as 10 min averages, with minimum and maximum on a data logger (EM50, Decagon Devices Inc., Pullman, WA, USA). Further, for energy balance measurements a net pyranometer and pyrgeometer (NR01, Hukseflux, The Netherlands) was installed in one of each type of the three plots 30 cm above the soil surface and connected to dataloggers (CR3000, CR1000, Campbell Scientific Inc., Logan, UT, USA) using a multiplexing system (AM25T, AM16/32, Campbell Scientific Inc., Logan, UT, USA). In two plots (Alulns-lamellas and control) a two dimensional sonic anemometer (WindSonic, Gill Instruments Ltd., UK) and a shielded temperature and relative humidity sensor (CS215, Campbell Scientific Inc., Logan, UT, USA) was installed 50 cm above the soil surface. Measurements were conducted every minute and stored as 10 min averages, with minimum and maximum on a datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA).

### 2.2. Brandbjerg, Denmark

The CLIMAITE manipulation (CO<sub>2</sub>, drought and temperature) was started in October 2005, here we only describe location and

temperature manipulation (refer to Mikkelsen et al., 2008 for detailed description). The experimental site is situated at Brandbjerg (55°53'N, 11°58'E) c. 50 km NW of Copenhagen, Denmark, on a hilly nutrient-poor sandy deposit. The site is a dry heath/grassland ecosystem consisting of 30–40 cm tall vegetation cover dominated by a grass (*Deschampsia flexuosa*, c. 70% cover) and an evergreen dwarf shrub (*Calluna vulgaris*, c. 30% cover) and an open moss cover beneath the canopy of vascular plants. The annual mean temperature is 8.0 °C and the annual mean precipitation is 613 mm (Mikkelsen et al., 2008). The warming treatment was conducted as 'passive nighttime warming' (Beier et al., 2004) by covering the plots with a curtain that reflects infrared radiation mounted on a light steel frame. The curtain was a white, water-proof woven acrylic cloth having 67% visible radiation reflection, 27% visible radiation transmission and 6% visible radiation absorption. The curtains were coiled on a beam and automatically operated according to preset conditions during the whole year:

- Day/night – curtains are pulled over the vegetation at sunset and retracted at sunrise.
- Rain – curtains are retracted in case of rain during the night (sensitivity <0.1 mm).
- Wind – the curtains are removed at high winds (>7 m s<sup>-1</sup>).
- Dewfall – the curtains are removed in case of dewfall in max 30 min, and then curtains are pulled over the vegetation again (Mikkelsen et al., 2008).

### 2.3. Porto Conte, Italy

The study area of Porto Conte is located in the Regional Park *Porto Conte – Capo Caccia* in the Capo Caccia peninsula (northwest Sardinia, Italy; 40° 37'N, 8° 10'E) (de Dato et al., 2008). The climate is semi-arid, characterized by a mean annual rainfall of 640 mm occurring mainly in autumn and spring, with a long dry period from May to August. The mean annual temperature is 16.8 °C, ranging from 7 °C (mean minimum temperatures in the coldest month) to 28 °C (mean maximum temperatures in the hottest month) (meteorological station of Fertilia Airport N 40°38'E 8°17'; altitude 40 m asl; distance to sea about 4 km; period of observation 1961–1990).

The experimental plots (6\*4 m each) were located in a fire-break opened in 1973, managed by controlled fire until 1990, then mechanically in 1991 and 1992. Since 1993, no other intervention has been done and vegetation started to colonize the bare soil. The vegetation cover is c. 80% constituted of *Cistus monspeliensis* L., *Helichrysum italicum* G. Don and *Dorycnium pentaphyllum* Scop with a max height of 1 meter. The warming experiment was conducted as night time warming (Beier et al., 2004) by covering the study plots with curtains of aluminum strips knitted into a high-density polyethylene mesh (Alu-mesh) during the night carried by a 1.5 m tall steel frame. The curtains moved along two rails placed on the shorter sides of the scaffolding. The operation of the curtains was automatically controlled by:

- Day/night – curtains are pulled over the vegetation at sunset and retracted at sunrise.
- Rain – curtains are retracted in case of rain during the night (sensitivity <0.1 mm).
- Wind – the curtains are removed at high winds (>10 m s<sup>-1</sup>).

The control treatment was delimited in the same manner as the warming treatments, except that they did not have any curtains. The opening and closing times of the curtains were recorded for each plot by switches (Mac-I) installed along the rails.

In each plot, the following microclimatic variables were continuously monitored: air temperature ( $T_{a20}$ ) and relative humidity (RH<sub>20</sub>) at 20 cm height from soil surface (Igromer HP100A, Rotronic,



CH); soil temperature at 10 cm depth (Ts10) and at 20 cm depth (Ts20) (LTN NR3, Tecno.El, IT); leaf wetness sensors (Decagon Devices, Inc., Pullman, WA, USA). Moreover, an in situ weather station measured air temperature and relative humidity (Igromer HP100A, Rotronic, CH), wind direction and speed (03002 Young, USA), global solar radiation (PYR SKS1110, Skye Instruments, UK) and precipitation (ARG199, Environmental Measurements, UK) at 2 m height. All the data were acquired every five minutes and stored in a datalogger (CR10X Campbell Scientific, Inc., USA) as half-hour mean values.

Temperature and relative humidity measurements of the air measured at +20 cm were used to determine air dew point,  $T_d$  (°C), using the August–Roche–Magnus approximation (Lawrence, 2005). The dew point temperature, representing a saturated vapour pressure of water in ambient air, was calculated as follows:

$$T_d = b \times \left[ a \times T_{a20} \times (b + T_{a20})^{-1} + \ln \left( \frac{RH_{20}}{100} \right) \right] \\ \times \left[ a - a \times T_{a20} \times (b + T_{a20})^{-1} + \ln \left( \frac{RH_{20}}{100} \right) \right]^{-1}$$

where the constants are  $a = 17.625$  and  $b = 243.04$  °C. The analyzed dataset consisted of hourly values of variables measured exclusively during nighttime and without rain events.

### 3. Results and discussion

For any installation with IR-reflective curtains in an ecosystem, the achieved warming effect (the temperature increase in the treatment plot relative to the control) depends on the stored energy during daytime (correlates positively with accumulated incoming radiation), convective heat loss during nighttime (correlates positively with wind speed), and the IR-reflective effect of the curtains compared to non-covered plots (correlates negatively with cloudiness because high cloudiness increases the atmospheric IR reflection in all plots and thereby reduces the additional effect of the curtains). Therefore, it is important to compare the results of any potential improvements of the passive nighttime warming with IR-reflective curtains at similar conditions in terms of incoming radiation at daytime, wind speed, and cloudiness. Fig. 1 illustrates how nighttime  $\Delta T$  of both soil (Fig. 1a and c) and air (Fig. 1b and d) increases with increasing accumulated PAR the day prior to the night, decreases with increasing cloud cover (Fig. 1a and b), and decreases with increasing wind speed (Fig. 1c and d).

#### 3.1. Potential improvements of the achieved “passive” warming by IR-reflective curtains

Warming with passive IR-reflective systems may be improved by increasing the heat storage during the day and/or by conserving the stored heat from daytime incoming radiation more efficiently. There are essentially three ways the stored heat can be conserved: (i) improving the long wave IR reflection by the curtains in order to reflect the IR radiation from the soil more efficiently and thereby improve the net radiation balance, (ii) reducing the lateral wind speed in order to reduce the convective heat loss and, (iii) insulating the curtains in order to reduce the conductive heat loss by transfer of heat through the curtain and loss to the atmosphere. Increasing the heat storage during the day can potentially be done by placing “heat bodies” in or near the plots.

##### 3.1.1. Insulation of curtains

Three of the six Alu-curtains at the Risø-DTU field site were manufactured with insulation material inside the lamellas (AluIns-lamellas). The performance of both Alu-lamellas and AluIns-lamellas were tested at the same time (Fig. 2a and b). The

**Table 1**

Long-wave (10–12  $\mu\text{m}$ ) IR-reflective properties of different curtain materials.

Material	Reflection (%)	Absorption (%)	Transmittance (%)
White fabric (CLIMAITE), old	10	90	0
Alu-mesh (Vulcan), old, shining site	50	40	10
Alu-mesh (Vulcan), old, dull site	10	80	10
Alu-mesh (Vulcan), new, shining site	70	28.5	1.5
Alu-mesh (Vulcan), new, dull site	15	83.5	1.5
Alu-lamella (DTU), new	96	4	0
Alu-lamella (DTU), old	95	5	0
Alu-lamella (chrome), new	91	9	0
Alu-lamella (anodized), new	3	97	0
Alu blanket, new	65	35	0
Gold blanket, new	70	30	0
Alu-flex (wall insulation), new	100	0	0
Alu-flex (wall insulation), new	96	4	0

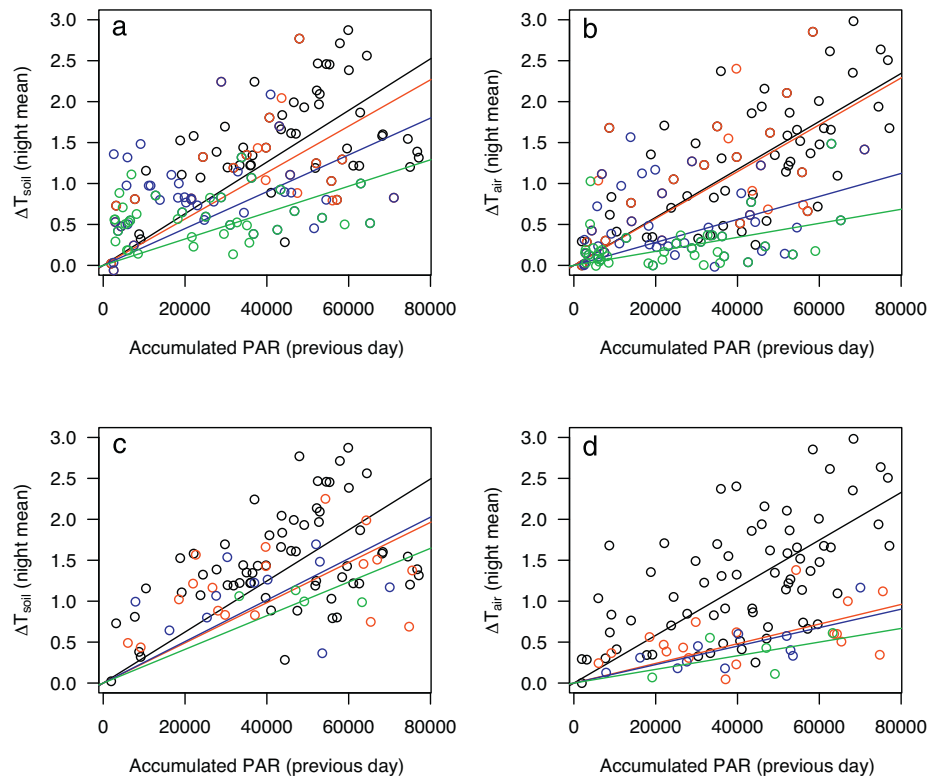
insulation of curtains clearly tended to increase  $\Delta T$  of air, by up to 0.5 °C when weather conditions resulted in a positive  $\Delta T$ , especially above 1.5 °C (Fig. 2d).

In a short period during winter, additional insulation by polystyrene block at nighttime at the Risø DTU site was applied to test if  $\Delta T$  could be increased even further. The  $\Delta T$  during this period was very low and there was no clear additional effect of the insulation on  $\Delta T$  (data not shown). The test of additional insulation was, however, carried out at winter time and three main problems with the passive nighttime warming technique during the period limits the conclusions: (1) the period was characterized with generally high cloudiness (i.e. small effect of reflective curtains), (2) condensation of humidity at the underside of curtains (i.e. water drops do not reflect far-IR, but absorb it), and (3) snow cover (i.e. no radiation of far IR from the ground to be captured during the day and therefore no heat accumulation to be reflected). It therefore remains unresolved whether additional insulation potentially could improve the heat storage under the curtains at other conditions.

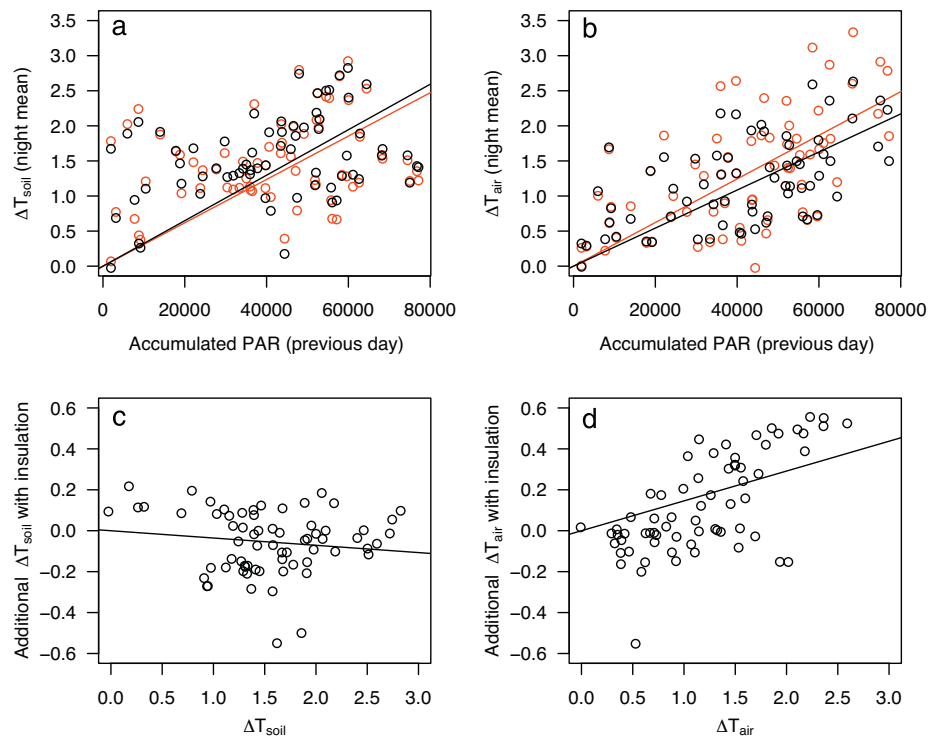
##### 3.1.2. Far-IR reflection by curtains

The far-IR (10–12  $\mu\text{m}$ ) reflection properties by small samples of different types of curtain materials were tested using a gold integrating sphere (Table 1). Based on these measurements we decided to test the potential of the hard aluminum lamellas (Alu-lamellas) with a far-IR reflection of 95–96% at the DTU-field site. This material was chosen because of its robustness and high far-IR reflection percentage. Other IR reflection/insulation materials, such as Air-flex and the commercially available rescue blanket, which would have high reflectivity, were believed to be too fragile for long-term field testing.

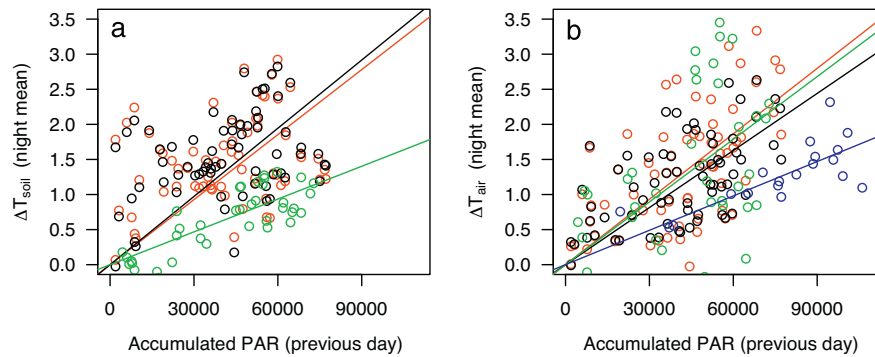
The achieved  $\Delta T$  for the lamellas were further compared at field conditions with the two types of curtains, that have been applied in the CLIMAITE and VULCAN projects: (i) white water-proof woven acrylic curtain (CLIMAITE: Brandbjerg, DK) with a far-IR reflection of 10%, (ii) Alu-mesh (VULCAN: Porto Conte, IT) with a far-IR reflection of 70% by new curtains and 50% by old and used curtains. In Fig. 3 are presented the achieved  $\Delta T$  of both soil and air at common conditions from the three different types of curtains at field conditions. As expected from the results in Table 1, there was a clear trend in the  $\Delta T$  of soil with higher achieved  $\Delta T$  under curtains with higher percentage of far-IR reflection (Fig. 3a). The trend was less



**Fig. 1.** The effect of Alu-lamella & AluIns-lamella curtains on difference between warming and control for soil ( $\Delta T_{\text{soil}}$ ) (a and c) and air ( $\Delta T_{\text{air}}$ ) (b and d) in response to accumulated PAR (proxy of incoming energy) covering data from all seasons from 3 Aug 2010 to 12 Sept 2011 at Risø-DTU. a and b show the warming effect for soil and air respectively dependent on cloud cover (classes of cloud cover, eights of sky; black: 0–1, red: 2–3, blue: 4–6, green: 7–8). c and d show the warming effect for soil and air respectively dependent on wind speed (classes of wind speed ( $\text{ms}^{-1}$ ); black: 0–1, red: 1–2, blue: 2–3, green: >3). Linear regressions are forced through origin and all are significant ( $p < 0.05$ ) with adjusted  $R^2$  values ranging 0.74–0.92.



**Fig. 2.** The effect of Alu-lamella curtains (black symbols) or AluIns-lamella curtains (red symbols) on  $\Delta T_{\text{soil}}$  (a) and  $\Delta T_{\text{air}}$  (b) in response to a proxy of incoming energy (accumulated PAR) covering data from all seasons from 3 Aug 2010 to 12 Sept 2011 at Risø-DTU. Linear regressions are forced through origin and all are significant ( $p < 0.0001$ ) with adjusted  $R^2$  values ranging 0.77–0.83. The additional  $\Delta T$  for  $T_{\text{soil}}$  (c;  $y = -0.04x$ ,  $R^2 = 0.12$ ,  $p = 0.002$ ) and  $T_{\text{air}}$  (d;  $y = 0.15x$ ,  $R^2 = 0.50$ ,  $p < 0.0001$ ) due to insulation of curtains are shown as a function of the measured  $\Delta T$  due to Alu-lamella curtains.

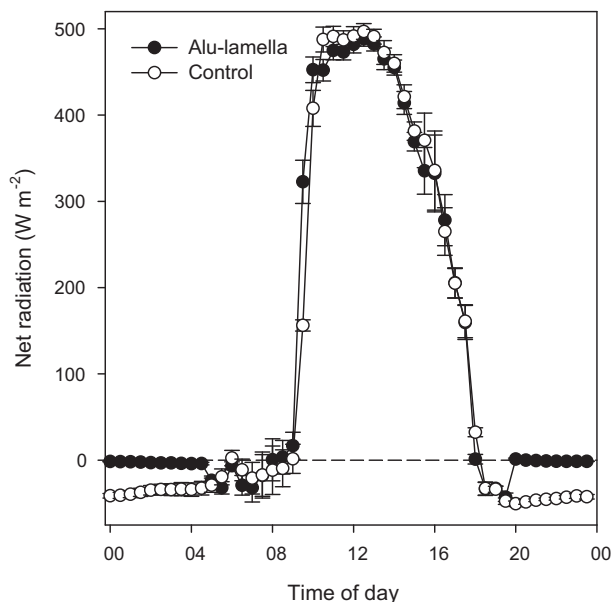


**Fig. 3.** The effect of Alu-lamella curtains (Risø-DTU, black symbols), Alu-lamella curtains (Risø-DTU, red symbols), white fabric curtains (Brandbjerg, green symbols), and Alu-mesh curtains (Porto Conte, blue symbols) on  $\Delta T_{\text{soil}}$  (a) and  $\Delta T_{\text{air}}$  (b) in response to a proxy of incoming energy (accumulated PAR) covering data from all seasons from 3 Aug 2010 to 12 Sept 2011. Linear regressions are forced through origin and all are significant ( $p < 0.0001$ ) with adjusted  $R^2$  values ranging 0.77–0.83.

clear for  $\Delta T$  in air as the white curtain performed as well as the Alu-lamellas (Fig. 3b). This may be a result of the radiation shield potential of the white curtain as it absorbs up to 90% of the long-wave radiation from the soil, which can be radiated back to both the ecosystem below and the atmosphere above.

### 3.1.3. Prolonging the IR reflection period

An example of the diurnal pattern in net radiation balance at a control plot and a passive night time warming plot (Alu-lamella) at the Risø-DTU field site is shown in Fig. 4. From this, the effect of employing the curtains at nighttime is obvious with a clear reduction in the radiation loss during night when the curtains are automatically rolled over the ecosystem. However, Fig. 4 demonstrates that there is already a substantial negative net radiation balance of the ecosystem ca. 1.5 h prior to sunset. This represents a heat loss that might potentially be retained if the curtains were activated prior to sunset. This was tested at the Risø-DTU field site and results are presented in Fig. 5. The results show that there is a potential to increase the air temperature by activating the curtains earlier, especially at high daytime accumulated PAR (Fig. 5b) and at high  $\Delta T$  of the air ( $\Delta T$  of 1 °C, Fig. 5d). Thus under favorable conditions, there appears to be a positive effect by activating curtains up to 1.5 h prior to sunset.



**Fig. 4.** Diurnal net radiation (averaged over six consecutive days in Apr 2011) at an Alu-lamella- and a control plot at the Risø-DTU field site (mean  $\pm$  SE).

### 3.1.4. Reducing wind speed

At the Risø-DTU-field site, the potential of raising  $\Delta T$  by reducing the convective heat loss by reducing the wind speed by vertical wind screens on three sites was tested. Reducing the wind speed resulted in an increasing additional  $\Delta T$  of the air, especially at high daytime accumulated PAR (Fig. 6b) and at high  $\Delta T$  of the air (Fig. 6d). However, this effect did not translate to an increased  $\Delta T$  of the soil (Fig. 6a and c).

### 3.1.5. Additional heat storing/releasing capacity

There was no detectable effect of increasing the heat storage by employing black water containers along the sites of the plots (data not shown). However, this could be due to the installed amount of heat storing capacity compared to plot size, which in our case could not be increased further without negative effects on the dense plant canopy. The net effect could also be quite small because the heat storage capacity from the shaded soil (by the containers) shall be subtracted the heat storage capacity from containers. At other field sites with relatively scarce plant cover, we speculate that solar panels and nocturnal heat release at the plot scale could be achieved by metal panels traversing the plot when used in combination with IR-reflective curtains.

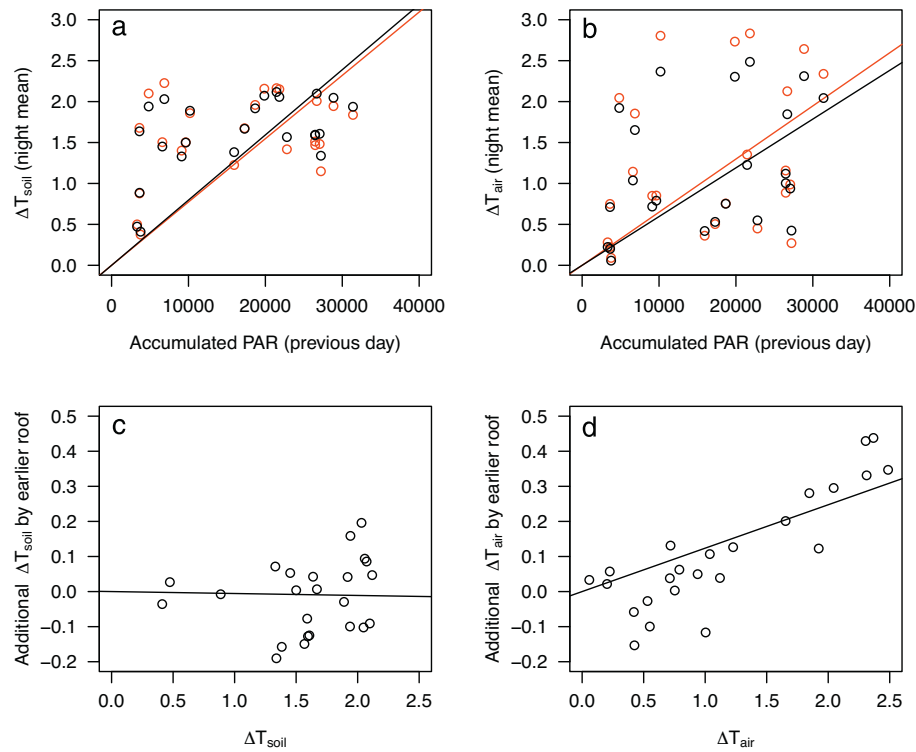
### 3.2. Concerns about side effects related to passive night time warming

As mentioned earlier, Aronson and McNulty (2009) concluded that the “passive” nighttime warming technique, as applied in the CLIMOR and CLIMAITE experiments, is one of the most realistic and applicable for field scale warming experiments. Amthor et al. (2010) raised several strong concerns in response to this. Here we provide experimentally based replies to these major concerns.

#### 3.2.1. Diurnal temperature range

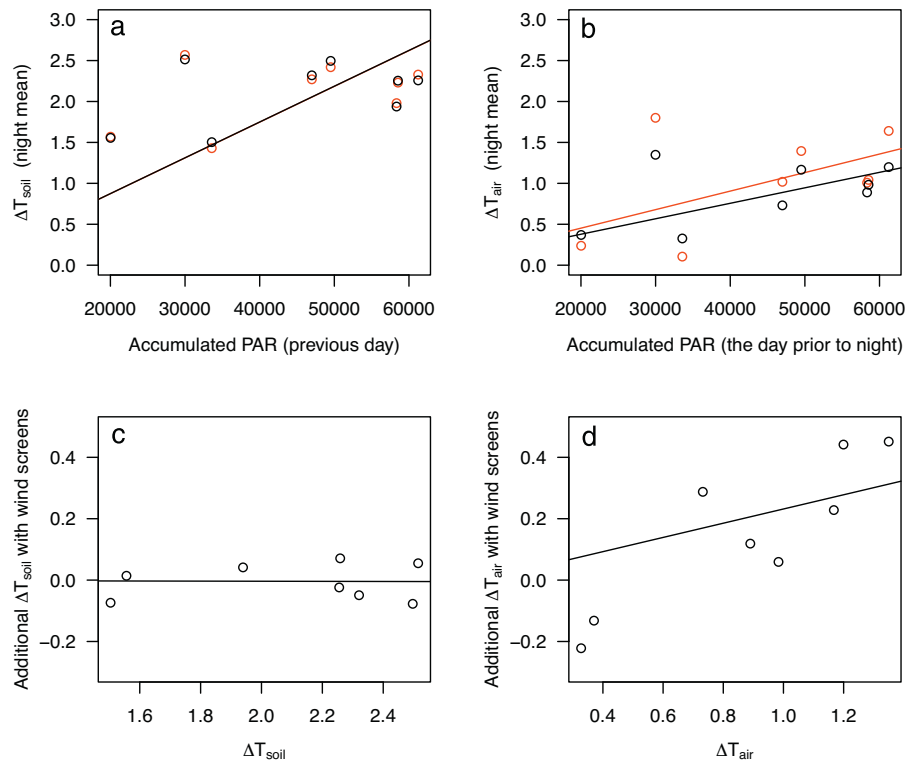
Amthor et al. (2010) challenged the premise of ‘nighttime-only’ warming and claimed it to be of ‘limited value to understanding effects of future warming on terrestrial ecosystems’. This is because, as Amthor et al. (2010) emphasized, the global trend (decline) in diurnal temperature range (DTR) disappeared after 1980. However, the stronger focus on nighttime warming relative to full diurnal warming is still supported by future temperature projections stating that ‘almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range’ (Meehl et al., 2007).

Further, as already proven by Mikkelsen et al. (2008) and Beier et al. (2004) “nighttime warming only” by the use of IR-reflective curtains does in fact not result in a *nighttime warming only*. Indeed, both air temperature and soil temperature of the experimental



**Fig. 5.** Effect of early activation of Alu-lamella curtain (ranging from ½ h to 1½ h earlier curtain out, red symbols) compared to that of normal timing of activation of curtains (black symbols) on  $\Delta T_{\text{soil}}$  (a) and  $\Delta T_{\text{air}}$  (b) in response to a proxy of incoming energy (accumulated PAR). Linear regressions are forced through origin and all are significant ( $p < 0.0001$ ) with adjusted  $R^2$  values ranging 0.61–0.81.

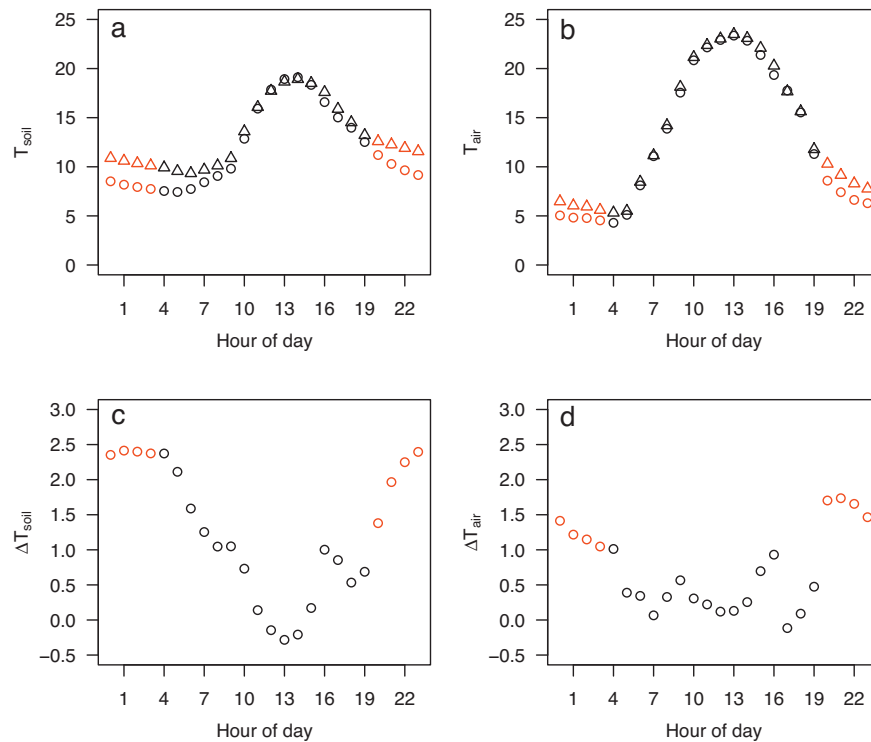
The additional  $\Delta T$  for  $T_{\text{soil}}$  (c;  $y = 0.0006x$ ,  $R^2 = -0.03$ ,  $p = 0.66$ ) and  $T_{\text{air}}$  (d;  $y = 0.12x$ ,  $R^2 = 0.73$ ,  $p < 0.0001$ ) due to early activation of curtains are shown as a function of the measured  $\Delta T$  due to normal timing of curtains.



**Fig. 6.** Effect of Alu-lamella curtain together with vertical wind screens (red symbols) and without vertical wind screens (black symbols) on  $\Delta T_{\text{soil}}$  (a) and  $\Delta T_{\text{air}}$  (b) in response to a proxy of incoming energy (accumulated PAR). Linear regressions are forced through origin and all are significant ( $p < 0.001$ ) with adjusted  $R^2$  values ranging 0.79–0.91.

The additional  $\Delta T$  for  $T_{\text{soil}}$  (c;  $y = -0.002x$ ,  $R^2 = -0.14$ ,  $p = 0.86$ ) and  $T_{\text{air}}$  (d;  $y = 0.23x$ ,  $R^2 = 0.57$ ,  $p = 0.012$ ) due to vertical wind screens are shown as a function of the measured  $\Delta T$  of curtains without vertical wind screens.





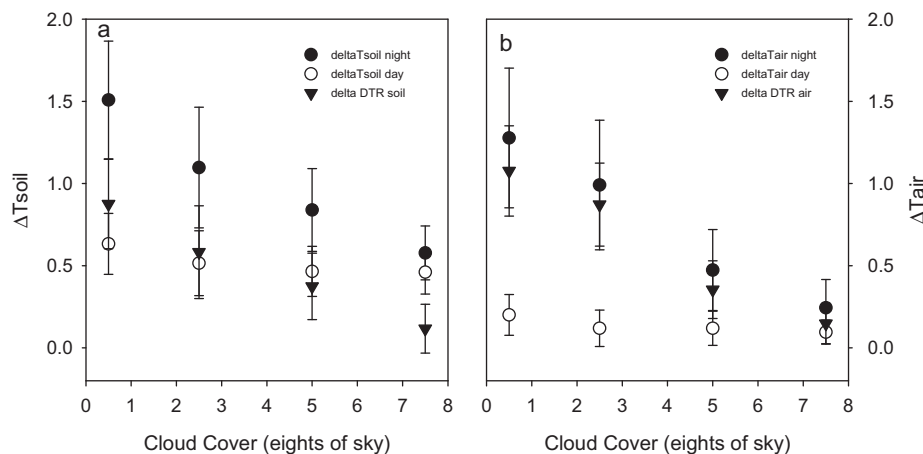
**Fig. 7.** Example of diel course of  $T_{\text{soil}}$  (a),  $T_{\text{air}}$  (b),  $\Delta T_{\text{soil}}$  (c), and  $\Delta T_{\text{air}}$  (d) at an Alu-lamella (triangles) and a control (circles) plot at the Risø-DTU field site. Red symbols represent nighttime and black symbols represent daytime. Data are averaged over six consecutive days in April 2011. Fig. 8.

plots experienced what could be termed a carryover effect into daytime, soil temperature in particular. This was reconfirmed in this study at the Risø-DTU field site (Fig. 7). On average the  $\Delta T_{\text{soil}}$  increased at daytime by c.  $0.5^\circ\text{C}$  (Fig. 8b), which apparently was enough to also warm the air by on average c.  $0.2^\circ\text{C}$  at daytime (Fig. 8a). Therefore, although there was a change in DTR (Fig. 8), it was lower than might otherwise be anticipated due to “night-time warming only” had there been no carryover effect. Finally, the change in DTR was changing with cloud cover (Fig. 8). Thus, night-time warming only may not necessarily be of limited value as stated by Amthor et al. (2010).

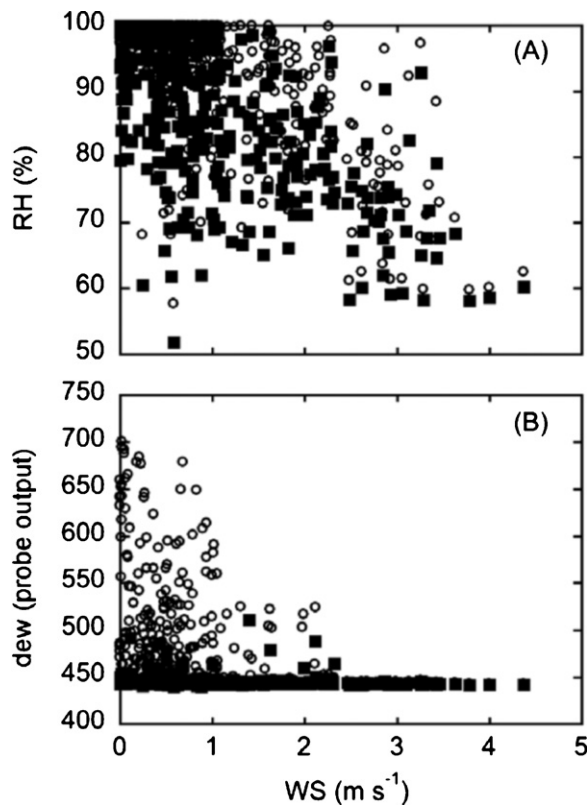
### 3.2.2. Relative humidity and dew (point)

Amthor et al. (2010) argued that IR radiation, as a means to warm ecosystems is not the same mechanism as would occur with global

warming. This was a comment to Aronson and McNulty (2009) who argued that an ecosystem warming ideally would use radiation warming as opposed to conduction and convection. However, Amthor et al. (2010) did not explain this concern but just claimed Aronson and McNulty (2009) to be wrong. We believe that the concern may relate to the concern raised by Kimball (2005), also mentioned by Amthor et al. (2010), that warming of surfaces by IR radiation as opposed to warming by convection and conduction may result in unwanted changes in water vapor pressure differences (VPD) between surfaces and air. However, Kimball (2011) state: “The most important aspect of warming experiments should be to warm the vegetation as expected in the future regardless of mechanism, and this can be achieved via infrared heaters with active computer control to maintain a constant canopy temperature rise above a corresponding reference plot”.



**Fig. 8.** Dependence of  $\Delta T_{\text{soil}}$  (night and day) and  $\Delta T_{\text{air}}$  (night and day) and  $\Delta T_{\text{DTR}}$  (a) and  $\Delta T_{\text{air}}$  (night and day) and  $\Delta T_{\text{DTR}}$  (b) as a function of Cloud Cover. Data (mean  $\pm$  SE) are from all seasons from 3 Aug 2010 to 12 Sept 2011 at Risø-DTU.



**Fig. 9.** Effects of wind speed (WS) on (A) relative humidity (RH) in the air measured at +20 cm inside the plots and (B) on dew formation (dew). Dew is expressed as the output of the leaf wetness sensors (LWS): the LWS outputs 445 raw counts when dry; varying amounts of water on the surface of the sensor cause a sensor output proportional to the amount of water on the sensor's surface. Open circle: control; closed square: warming.

In this study, we found at Porto Conte that the IR-reflective curtains decreased the RH measured during the night by 5% ( $p < 0.0001$ ) and increased the nighttime air temperature by  $1.1^{\circ}\text{C}$  ( $p < 0.0001$ ). However, dew point remained unaffected ( $p < 0.38$ ) and there was no relation between nighttime RH or nighttime dew and incoming daytime radiation. The RH did not reach saturation during windy nights (about  $\text{WS} > 3 \text{ m s}^{-1}$ ) in either treatments (Fig. 9a). Similarly, at nighttime with high wind speed no dew was formed in both control and warming (Fig. 9b). However, the effect of reflective curtains on RH and dew (leaf wetness) was not affected by the cloud cover. Increasing cloud cover significantly changed the dewpoint on average by  $+1.4^{\circ}\text{C}$ ; it was higher under covered (cloud cover  $> 2$ ) than under clear (cloud cover  $\leq 2$ ) sky conditions, independent on the treatments (Table 2).

In contrast to the results reported here from Porto Conte, Beier et al. (2004) reported a general increase of air RH by 0–5% by reflective curtains. Thus, we conclude that, although the employment of IR-reflective curtains at nighttime may alter the RH, it is a small

change and not always in the same direction. In addition, curtain treatments are only active during nighttime when the stomata is mainly closed, so the increase in evapotranspiration would be smaller than that of systems that warm also in the daytime.

### 3.3. Perspectives

Here we have demonstrated some feasible avenues for increasing the achieved  $\Delta T$  when using IR-reflective curtains at field scale: (i) improving the long wave IR reflection of the curtains, (ii) reducing the lateral wind speed, and (iii) insulating the curtains. Because of the achieved  $\Delta T$  by the use of IR-reflective curtains is so dependent on climate (incoming energy at daytime, cloud cover, and wind speed) it is obvious that the net warming effect of IR-reflective curtains will vary along geographical and thereby climatic gradients.

Lastly, although it may seem counterintuitive, we speculate that in long-term field experiments, less use of the curtains under conditions with no effects or cooling effects may indeed result in an improved overall increase in temperature. The reasoning is that curtains may lose some their effect by wear and tear due to wind damage of the fabric and/or the roller system. Thus, more 'intelligent' employment of curtains within certain boundaries of weather conditions may be a way forward.

### Acknowledgements

The authors acknowledge the financial support by the European Union FP7- Infrastructure-2008-1 project INCREASE, contract no. 227628. The CLIMAITE project was financially supported by the Villum Kann Rasmussen Foundation. CLIMAITE project support was also received from Air Liquide and DONG energy. Svend Danbæk, Poul T. Sørensen, Nina Wiese Thomsen, Andreas Fernquist and Preben Jørgensen are thanked for their effort in keeping the Danish research sites running. We thank Bent Vraae Jørgensen, Danish Meteorological Institute for providing cloud cover data.

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**Table 2**

Effects of IR-reflective curtains on humidity parameters.

	Cloud cover $\leq 2$		Cloud cover $> 2$	
	Control	Curtain	Control	Curtain
RH	93.7 A	87.2 * A	92.3 A	88.1 * A
LW	481.0 A	444.7 * A	488.7 A	446.4 * A
Td	15.6 A	15.7 ns A	16.6 B	16.9 ns B

RH: relative humidity; LW: leaf wetness; Td: dew point. \* = significant difference between control and warming. Upper case letters = comparison between cloud covers in each treatment.

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